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Predicting Fatigue in Reactor Components using Artificial Intelligence/Machine Learning and Computational Mechanics

Subhasish Mohanty, Joseph T. Listwan
Materials Research Pathway

The effects of environment on fatigue resistance of materials used in operating pressurized water reactor (PWR) and boiling water reactor (BWR) plants require an assessment of environmentally assisted fatigue under extended service conditions. Fatigue modeling of a reactor component is a complex problem due to time-dependent cyclic hardening/softening, the load-sequence effect, and the effects associated with a corrosive environment. Because of this complexity, fatigue is traditionally modeled using experimental data. However, the test-based empirical approach often requires hundreds of fatigue tests to model the intermixing failure modes even for a single material system. To address these limitations, we are developing a hybrid modeling framework for predicting the time-series structural states of nuclear reactor components. This is based on combining artificial intelligence (AI)/machine learning (ML) techniques with computational mechanics. In 2020, we developed an AI/ML guided fatigue testing methodology to improve the U.S. environmental fatigue testing capabilities [1]. Conventional low-cycle fatigue evaluation of nuclear reactor components requires constant-amplitude-strain-controlled fatigue test data (e.g., strain versus life [ε-N] curves). However, controlling strain in a PWR water test can be a great challenge, since an extensometer cannot be placed in a narrow autoclave due to the lack of space inside an autoclave. The difficulty in using an extensometer in a PWR loop led us

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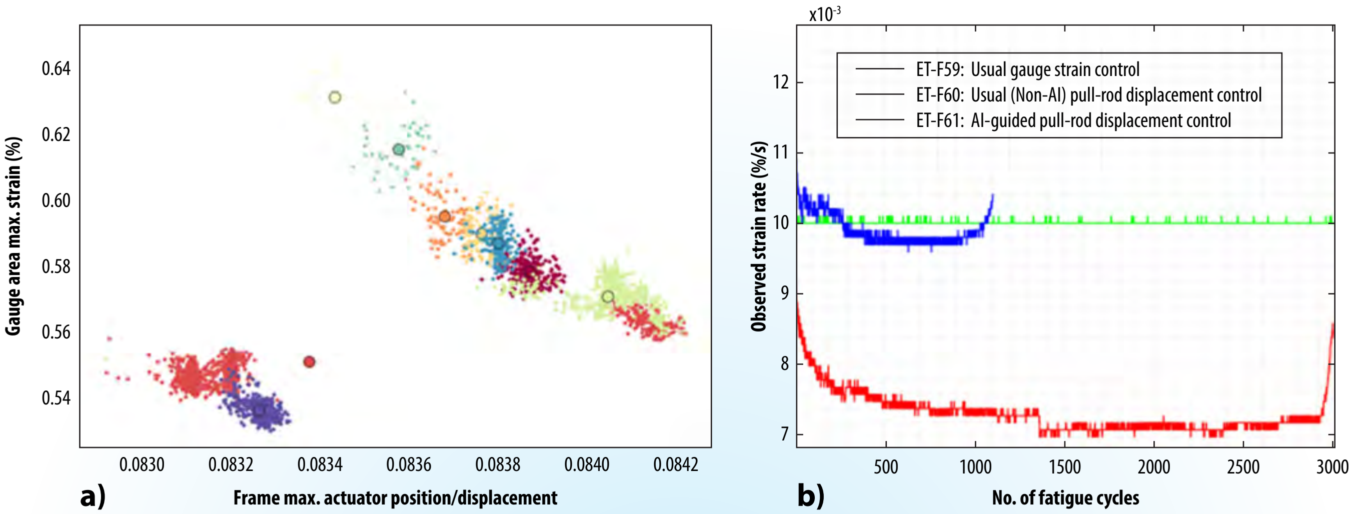

Figure 1. (a) Clustered fatigue test data. (b) Observed strain rates in non-AI and AI-guided fatigue tests and their comparisons with respect to the usual strain control test-based strain rates.

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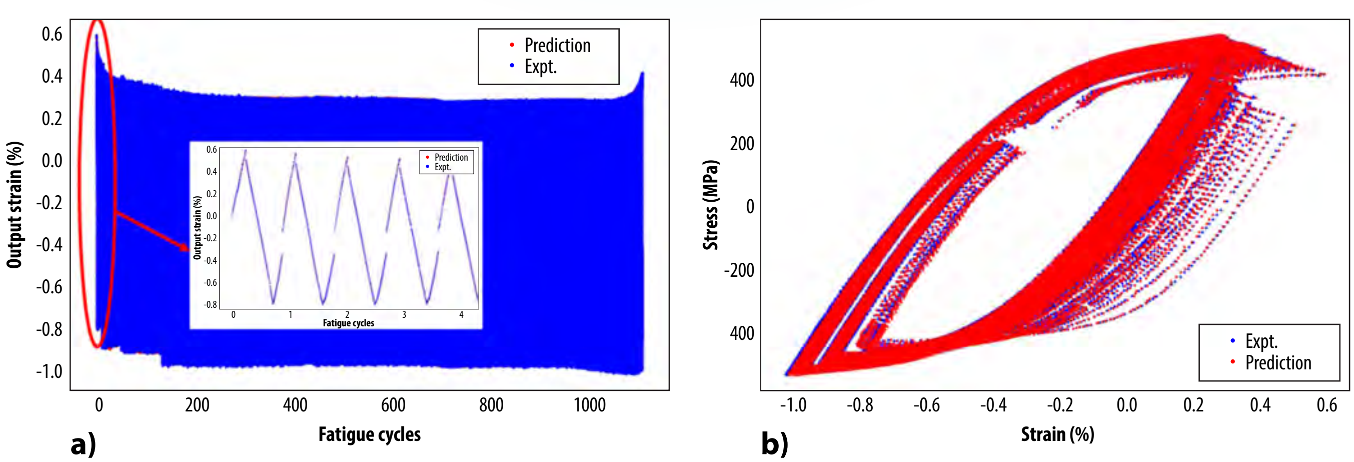
to use an outside-autoclave displacement sensor, which measures the displacement of a pull-rod-specimen assembly. However, in our earlier study based on in-air fatigue test data, we found that a pull-rod-control-based fatigue test can lead to substantial cyclic hardening/softening resulting in different cyclic strain amplitudes and their rates compared to the target conditions. In 2020, we applied a k-Mean clustering technique to improve the pull-rod-control-based fatigue test method, achieving reasonable gauge-area strain amplitudes and rates. Figure 1(a) shows the grouping of fatigue test data into different clusters based on different sets of test inputs that were selected to maintain a steady-strain amplitude and rate in a pull-rod-displacement-control test. Figure 1(b) compares the strain rate observed under a usual strain control test and under usual (non-AI) pull-rod displacement control and AI-guided pull-rod displacement control fatigue tests. The result shows the AI-guided test improves the strain rate as compared to the usual pull-rod displacement control test.

In addition, we also developed AI/ML-based data-driven models for predicting time-series strain from other sensor measurements, such as load cell, frame pull-rod displacement, and actuator displacement sensors [1]. The framework was trained and validated against in-air fatigue test data for which the strain was measurable. The validated model was used to predict strains in a

Figure 2. (a) Experiment versus AI/ML model predicted cyclic strains in a dissimilar-metal-weld (508LAS-316SS) subjected to hundreds of fatigue loading cycles. (b) Corresponding hysteresis curves.



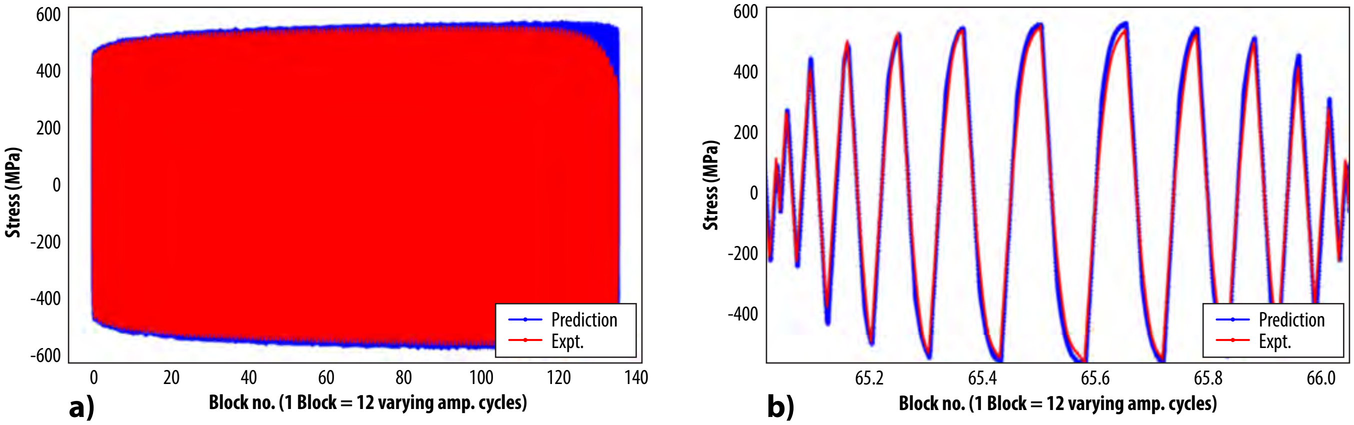


Figure 3(a) Predicted versus experimentally observed cyclic stress for the entire fatigue life of 82/182 DMW specimen subjected to variable amplitude loading. (b) Magnified view of (a) at half-life.

reactor-coolant fatigue test loop in which direct strain was not measurable. Although the original aim of this research was to improve the U.S. environmental testing and measurement capabilities for conducting fatigue tests in a high-temperature-pressure reactor-coolant flow environment, a similar approach can be used for predicting strain in an actual reactor component in which strain cannot be directly measured due to accessibility constraints. Figure 2 shows examples of model validation results.

To address the issue of data insufficiency, which is more pervasive for weld metals, the hybrid AI/ML and computational mechanics based predictive modeling was applied to model fatigue in dissimilar-metal-weld (DMW) 82/182 [1]. Figure 3 shows some sample results of the predicted versus experimentally observed cyclic stress for the entire fatigue life of a DMW specimen. For the shown test case, the cyclic stress-strain curves were first estimated using AI/ML-based TensorFlow library. Then, the resulting cyclic stress-strain properties were used for predicting the time-/cycle-dependent stresses using a cyclic-plasticity based on the mechanistic or physics model. Predicting stress and strain in reactor components using AI/ML and computational mechanics is on a path to provide more accurate results that will improve light water reactor (LWR) sustainability.

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Outstanding Researcher Award

Chad L. Pope
Risk-Informed Systems Analysis Pathway,
Idaho State University

Idaho State University (ISU) Office of Research has selected Dr. Chad Pope to receive an Outstanding Researcher Award for 2021. Dr. Pope is a professor and Department Chair in ISU's Nuclear Engineering Department. He joined ISU in 2013 following a distinguished 24-year INL career. Pope's research dovetails with the goals of the LWRS Program and centers on improving nuclear power safety, reliability, and economics. He also is responsible for the creation of the Versatile Economic Risk Tool (VERT), which addresses power generation risk by examining plant components supporting electricity generation. VERT integrates traditional risk analysis software, component reliability data, and data analysis software to identify trends in equipment performance that lead to electricity production impacts. Over the last six years, ten graduate students have completed their master's degree in support of these research projects. Additionally, two students have completed their PhD through research work related to these projects. These students have entered the nuclear workforce and are further contributing to the success and advancement of nuclear power.

Testing of Person-Passable Openings that Intersect a Security Boundary

W. Gary Rivera
Physical Security Pathway

The Physical Security Pathway performs research and development (R&D) to develop and enhance methods, tools, and technologies that advance the technical basis needed to optimize and modernize a nuclear facility's security posture. One research area, being performed in conjunction with the Nuclear Energy Institute and Light Water Reactor Sustainability (LWRS) Program researchers at Sandia National Laboratories (SNL), is testing to reevaluate and redefine the minimum passible opening size through which a person can effectively pass and navigate. These tests are on both simple two-dimensional (up to 36-inch in depth) and more complex three-dimensional (longer lengths and changes in direction) configurations. The primary impact of this effort is to define the scenarios in which an adversary could successfully pass through a potentially complex opening, as well as define the scenarios in which an adversary would not be expected to successfully traverse a complex opening. This systematically tested data can then be used to support risk-informed decision-making. At its inception, the project intended to investigate openings that could be found to intersect security boundary layers (e.g., drainage culvert), but through careful experimental design, the testing seeks to further understand the delay characteristics of engineered openings (e.g., piping systems), as well as potential breach points (e.g., cutting through a wall or door).

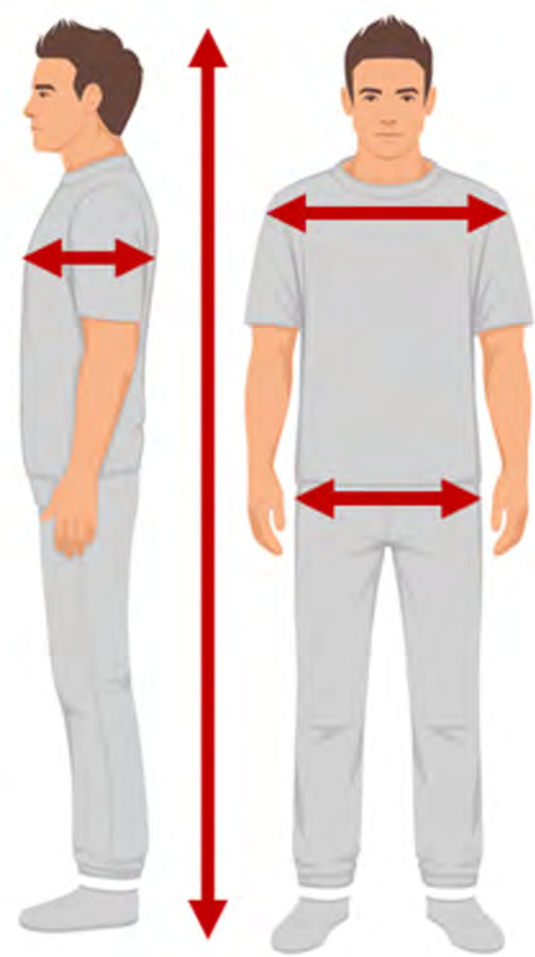
In determining the minimum passable opening size that an adversary could exploit, the following questions should also be asked: (1) Does this opening increase risk or provide an opportunity to an adversary? (2) If so, how can this opening be exploited? (3) How much time does it take for the opening configuration to be exploited in various scenarios? (4) What are the limitations of this exploitation?

The industry has an established minimum passable opening size, and while these dimensions have been the accepted standard for decades, there is little information to their origin, correlation to the adversary size that could exploit the minimum passible openings, or how much delay is generated by openings of different sizes. This study seeks to not only determine the smallest area in which an adversary can pass, but also to correlate passable apertures with statistical person size data for various U.S. military populations, and how fast they can successfully navigate different configurations.

As one can imagine, a plethora of variables or factors exist that can influence both the minimum passable opening size, as well as the time or rate at which an adversary can successfully traverse a barrier. The size of the person attempting to breach the opening will be a primary influence on how small a hole they can squeeze through. As shown in Figure 4, there are critical dimensions of the human body that cannot be easily manipulated, such as hip width, chest depth, and head diameter. Conversely, there are other adversary factors that are less fixed, such as choice of clothing, body armor, or equipment and weapons being carried that could be dragged behind during the passthrough in order to successfully traverse the opening. The time and rate that it takes to successfully navigate a longer opening, such as a pipe, will depend on variables such as person size, pipe diameter, internal surface friction, and the ability to navigate corners.

Personality variables like claustrophobia, mental fortitude, determination, etc., are not being considered as it is

Figure 4. Human hip and chest depth are data of interest.



assumed a determined adversary will mentally prepare and allow themselves to be placed in uncomfortable and stressed positions in order to achieve their goal.

Our test team is seeking to include both male and female test participants that represent a number of human factors databases with large sample size populations. While it is expected that a low percentile of subjects will likely determine the minimum passible opening in this study, participants in the 50th and 75th percentiles may have different performance characteristics for traversal rates and differences in the ability to drag a bag of equipment behind them in a longer and more complex pipe.

All testing is to take place at the SNL's Sandia Access Delay lab and will be broken into two distinct activities: (1) two-dimensional testing; and (2) three-dimensional testing. An example of two- and three-dimensional testing configurations are shown in Figure 5 and Figure 6, respectively. For our two-dimensional tests, participants will navigate through a rectangular opening that can be varied incrementally in both horizontal and vertical major dimensions, where a circular aperture will be used to simulate a round hole. The depth of the two-dimensional fixture is approximately 3.5-inches, which approximates a thin wall section. In addition to the rectangular opening, each participant will attempt to traverse a series of pipe sections of varied diameters, which are each 36-inches long.

The three-dimensional testing will utilize modular circular pipe and square conduit sections with predetermined internal dimensions. These tests can be configured to provide a long 24-foot straight section, an "L" with a single 90° elbow, or a jog section with two 90° elbows.

Safety of our participants is of utmost importance and consideration. Each will be chosen from a pool of volunteers who will be recruited from SNL and fully informed as to the test objectives, the safety precautions in place, and screened for risk factors such as claustrophobia. Because this testing is primarily a test of a person's ability to conduct a given task, our test team is working with the Sandia Human Studies Board to fully vet the processes, procedures, test fixtures, data collection, and participant safety. The test fixtures designed for this test series are designed to be quickly opened or disassembled to allow a test participant to be freed from the apparatus if they happen to become stuck.

SNL's Access Delay Department has a long history of conducting these types of access delay tests and employs a range of experienced engineers and technologists who each bring unique skillsets, including experienced breachers, computer modelers, explosive experts, and security professionals. Together, there is broad expertise in all aspects of physical security systems R&D, as well as integrated, engineered systems design and implementation.

Figure 5. Proposed two-dimensional opening test setup.

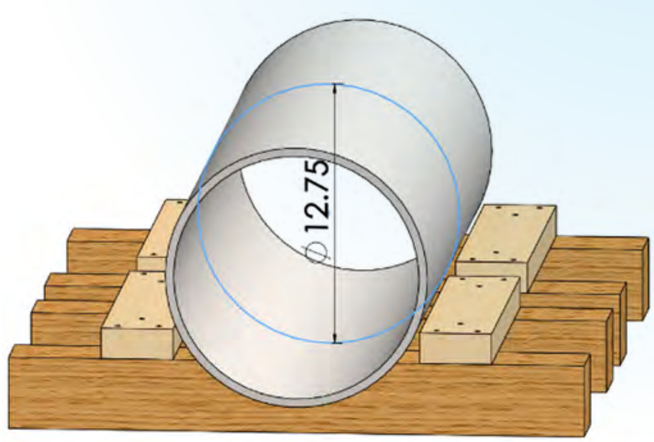
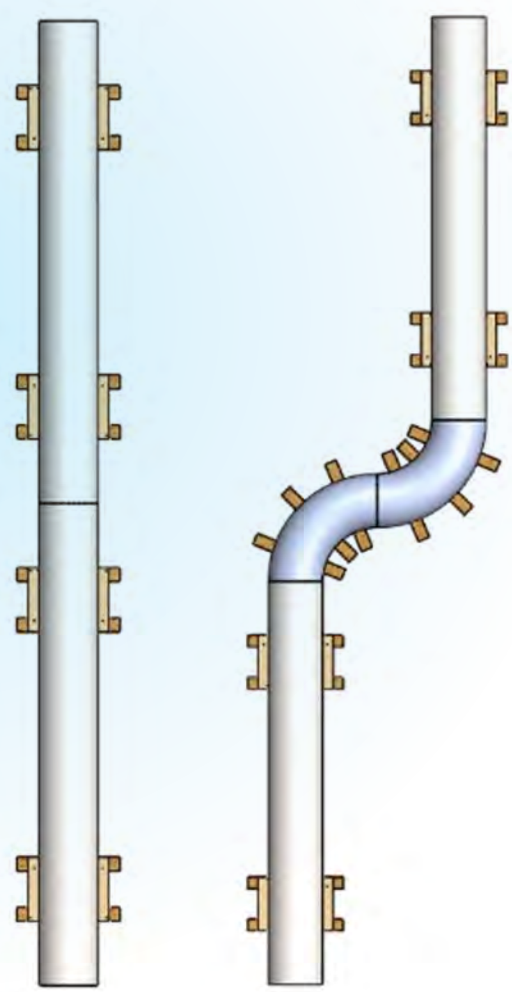
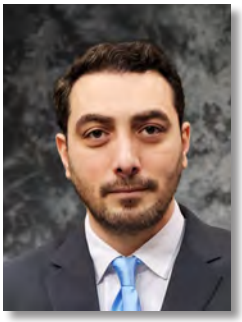


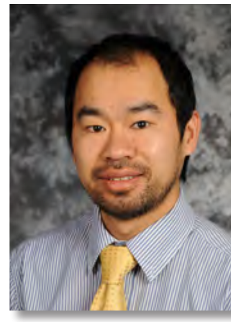
Figure 6. Proposed three-dimensional opening test setups.



Plant Modernization Technologies Move From R&D to Commercialization



Ahmad Al Rashdan, L. Michael Griffel, Roger Boza
Plant Modernization Pathway




Roger Lew, Dakota Roberson
University of Idaho

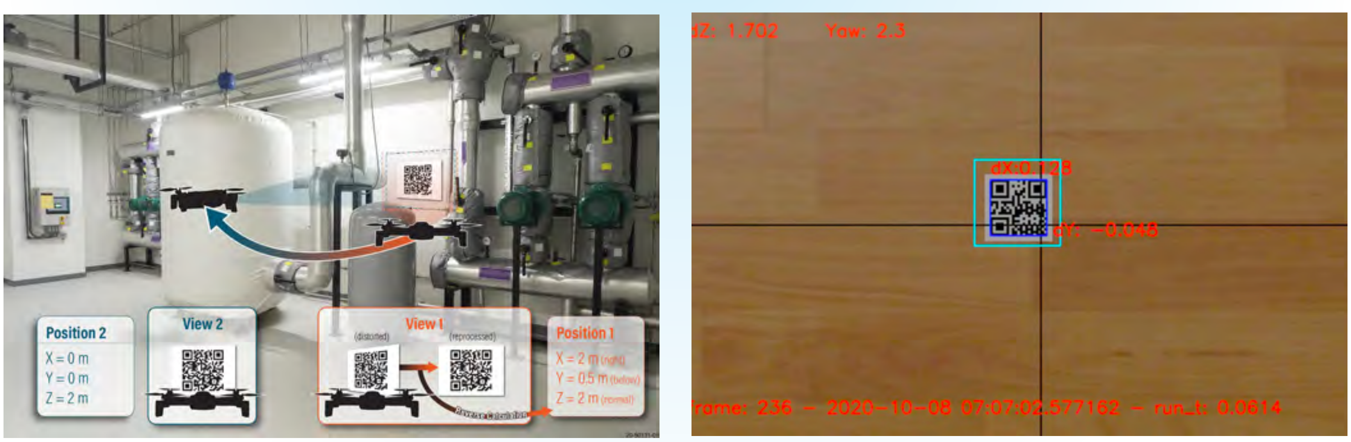
As part of the LWRS Program mission to modernize nuclear power plants, a team has developed several technologies to automate plant support activities leveraging recent advancements in AI. Three example technologies are the (1) Route Operable Unmanned Navigation of Drones (ROUNDS), (2) automated gauge reading, and (3) fire watch automation. All three technologies have matured through R&D and are currently advancing towards commercialization and deployment in nuclear power plants through multiple industry partners.

ROUNDS enables a drone to determine its' own location with a high degree of accuracy using visual landmarks. Using this self-location technique, it can move rapidly and accurately along a path without assistance from geospatial positioning systems. This technology can be used to automate operator and security rounds, radiation monitoring, inspections, surveys, and field monitoring in a nuclear power plant.

ROUNDS is a suite of software algorithms that empower a drone to follow a trajectory mapped out by Quick Response (QR) codes. Dynamic position tracking enables continuous updates to the drone's relative location. The technology exploits the imaging and communication capabilities of readily available commercial drones. It uses a drone's standard camera to capture QR code images intentionally placed in fixed locations throughout the plant that are in the drone's operating environment. The QR code image depends on a drone's relative position with respect to the code, as shown in Figure 7. If the camera evaluates a skewed QR code when the drone's line-of-sight is not directly perpendicular to the code, the ***ROUNDS*** algorithms infer the drone's location relative to the QR code, which has a location known as "a priori." This makes it possible to determine the drone's location in the environment within roughly an inch of its true position—a significant improvement over the few feet possible otherwise—and to fly faster through its route, which enables the drone to cover long distances on a single battery charge.

With its exact location routinely calculated, the drone can move along a set trajectory toward the next QR code in its

Figure 7. The drone view of the QR code is used to determine the drone's relative location to the code.



path. ROUNDS recently reached the 2020 R&D 100 award finalists list.

Automated Gauge Reading recognizes and reads distant measurements from gauges in a video stream. Because most U.S. nuclear power plants were built between 1960 and 1990, most of the gauges use analog instruments, whose values or states are not captured in digital form, requiring operators to manually monitor and log data periodically. Automating the gauge reading process replaces the need for staff to log data periodically in the control room and the field, provides temporal high-fidelity data streams needed to enable continuous online monitoring, can be leveraged for training scenarios replication and engineering, and enables automated gauge calibration—especially in control room panels—because the process can detect gauge drift by comparing it to reference points, whether the instrument measurement has previously been archived in the plant computer, and any historical behavior.

Figure 8. Uses of automated gauge reading at oblique angles.

Several vendors have developed retrofit solutions that can be installed on a gauge to digitize the analog value directly facing a gauge [1]. The limitation of this approach is that it requires one device per gauge. Often, gauges are centered in groups. Additionally, the use of these technologies in control room panels complicates the installation of a device, and directly obstructs an operator's view of the analog display.

The technology gap targeted by this effort was a method to read gauges at oblique angles, which led to the development of software that can identify a gauge from its surrounding environment in an image or video and quantify its orientation and position in space to autonomously read it. This enables the technology to be integrated with any device that has a camera with satisfactory specifications, as shown in Figure 8.

Fire Watch Automation leverages recent AI innovations. Throughout the nuclear power industry, the fire watch level being performed varies depending on a plant's condition. As such, if a plant requires a frequent fire watch, its cost burden may be high. Based upon sensor technology advancements, as well as increased video and image data capture over recent years, a great potential exists for automating fire or smoke detection in real-time using remote sensing. The LWRS Program developed an approach leveraging AI models, such as Convolutional Neural Networks [2], which can emulate the human detection of fire in a video stream. An image processing method was also developed to filter the video frames as they are evaluated by AI [3].

Fire watch automation technology is a software that can be applied to a video stream (from any camera) provided the video stream meets minimum resolution requirements that are associated with the specific application. Because fires can be a different color, form, size, and duration depending on the application, the training dataset for fire detection is continuously expanded to reflect as many potential fire types as possible. A regulatory evaluation of deploying the technology in a nuclear power plant is being performed as part of the LWRS Program effort.

Watch this LWRS Program ROUNDS video to learn more.

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Status of Risk-Informed Multi-Physics Best Estimate Plus Uncertainty Method Development



Yong-Joon Choi, Carlo Parisi, Svetlana Lawrence
Risk-Informed Systems Analysis Pathway

Kostandin Ivanov
North Carolina State University

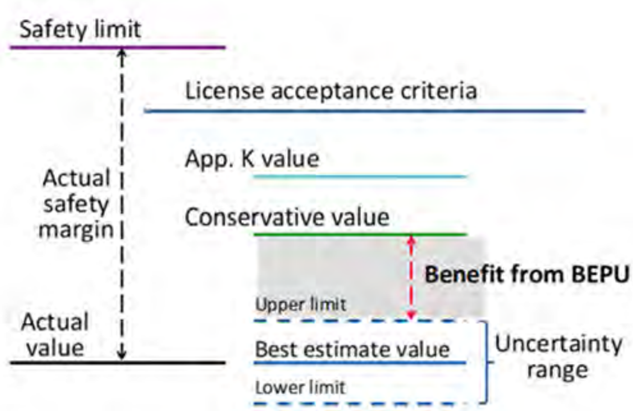
The Risk-Informed Systems Analysis (RISA) Pathway mainly uses the probabilistic safety assessment (PSA) approach to reduce conservatisms in LWR safety margins. A complementary approach that could further reduce unnecessary conservatisms is to combine the PSA approach and uncertainty analysis methodologies to cover multi-physics phenomena (e.g., neutronics, fuel performance, thermal-hydraulics) during safety analysis. This approach is called the risk-informed multi-physics best estimate plus uncertainties (BEPU) method. The RISA Pathway is exploring the BEPU method in its industry engaged demonstration projects by: (1) upgrading RELAP5-3D, the best estimate thermal-hydraulics code, to allow quantifying uncertainties from major physical phenomena during a loss-of-coolant (LOCA) scenario; and (2) by participating in an international benchmark program led by the Nuclear Energy Agency of the Organization for Economic Cooperation and Development (OECD-NEA) for the validation and use of actual nuclear power plant operational data.

Sources of uncertainties include unavoidable errors introduced by assumptions and approximations used in thermal-hydraulics computational tools. By using a fully validated computer code with realistic data from experiments and operations, the BEPU method can quantify computational uncertainties. The BEPU method will, therefore, reduce conservatisms and increase safety margins during accident analysis. Figure 9 shows an example of a safety margin that can benefit from the use of the BEPU method. The BEPU method can provide additional safety margin (the shaded area in Figure 9) compared to a conservative approach, even measuring margin from upper limit of uncertainty range. For this reason, the U.S. Nuclear Regulatory Commission (NRC) allows licensing applications to use the BEPU method [1] which will also enhance the economics of U.S. nuclear power plants. This method is also applied to licensing for more than 20 nuclear power plants around the world.

Upgrade of RELAP5-3D for BEPU Analysis

RELAP5-3D, developed at Idaho National Laboratory (INL), is a best estimate nuclear power plant thermal-hydraulics analysis code that is used to evaluate safety margins. The general approach to quantify uncertainty is to apply a probability density function (PDF) to the field equation, which solves the physics. However, previous researchers could only apply PDF to the input file, which would generate additional uncertainties. The RISA-proposed approach allows the PDFs to be applied directly to the constant in the field equation source code. This approach produces a better-defined uncertainty band. The PDF can be set through a data-sampling tool such as the Risk Analysis Virtual EnviroNment (RAVEN). The RELAP5-3D source code was modified to receive the PDF from RAVEN. The reflood phase of a LOCA scenario was used for the demonstration, and clad temperature was compared. Shown in Figure 10 , the uncertainty band mostly covers data from experiments and non-BEPU simulations. It is noted that the temperature drop showed a large discrepancy between the experiments (near 100 seconds) and the non-BEPU simulation (near 80 seconds), which may lead to a misjudgment during a safety analysis. However, the BEPU method identified that

Figure 9. Comparison of safety margins between Appendix K, conservative and BEPU.



the discrepancy is due to the computational uncertainties. This is an example of the benefit from using the BEPU method that an analyst can correctly predict an acceptable range of physical phenomena changes.

OECD-NEA International Benchmark Program on the Multi-Physics BEPU Method

Since 2007, the OECD-NEA has been conducting research to understand multi-physics uncertainties using actual plant operation data from the following: Three Mile Island Unit 1 (PWR), Peach Bottom 2 (BWR), and Kozloduy Unit 6 and Kalinin Unit 3 (VVER, a Russian PWR). The research found that the uncertainties in neutronics are mainly from the covariance nuclear data libraries. The research is continuing for the coupled neutronics, kinetics, and thermal-hydraulics, including their feedback effects. The study also considers consistency between computational tools, and uncertainty from the scaling effect during modeling and simulation.

BEPU Application for Transition from Deterministic to Risk-Informed Approach

The BEPU method supports the transition from deterministic to a risk-informed approach. For example, safety analyses of nuclear fuel with higher enrichment and extended burnup cannot be completed using a purely deterministic approach because of the concern of fuel fragmentation, relocation, and dispersal (FFRD). With the current burnup limit of 62 GWd/MTU, the FFRD analysis is not required in the current deterministic LOCA analysis to meet the Code of Federal Regulation (CFR) Title 10 (10 CFR 50.46a) acceptance criteria. However, with the new limit of 75 GWd/MTU, the FFRD issue must be addressed. This phenomenon is very complex and not well understood, and more importantly there is a lack of data. As such, it has become an impediment to licensing for burnup extension. The risk-informed approach uses the process defined in NRC's guideline to determine the contribution of LOCA-induced FFRD to plant risk, by quantifying core damage frequency and large early release frequency, and burnup extension [2]. This could be the basis for seeking the NRC's approval to extend current practice of not including FFRD in the design-basis LOCA analysis performed following the 10 CFR 50.46 criteria. The goal of the risk-informed approach is to demonstrate that FFRD with peak rod average burnups in the range 62 to 75 GWd/MTU caused by LOCA events is of sufficiently low risk that it does not need to be included in the design-basis analyses of LOCA. The BEPU methodology supports risk-informed approaches to complex safety evaluations by providing a better understanding of the accident scenario conditions and associate uncertainties.

References

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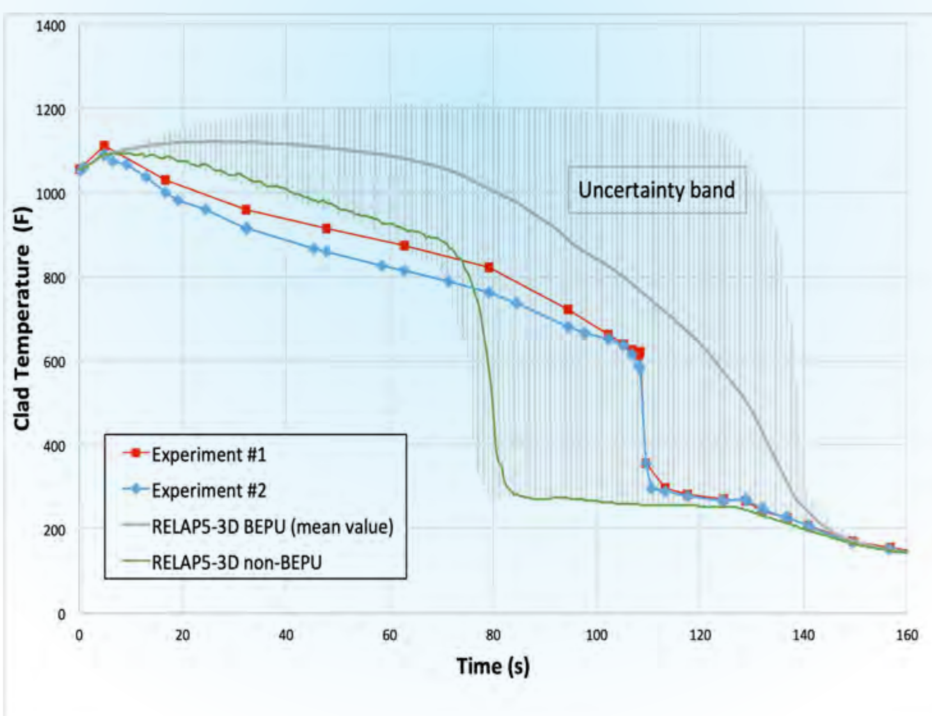
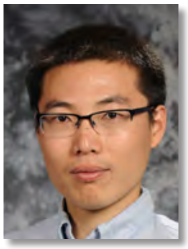
Figure 10. Cladding temperature behavior and uncertainty band at upper part of core.



Flexible Enterprise Risk Analysis Framework Software is Free and Open Source





Congjian Wang, Diego Mandelli
Risk-Informed Systems Analysis Pathway

David P. Morton
Northwestern University

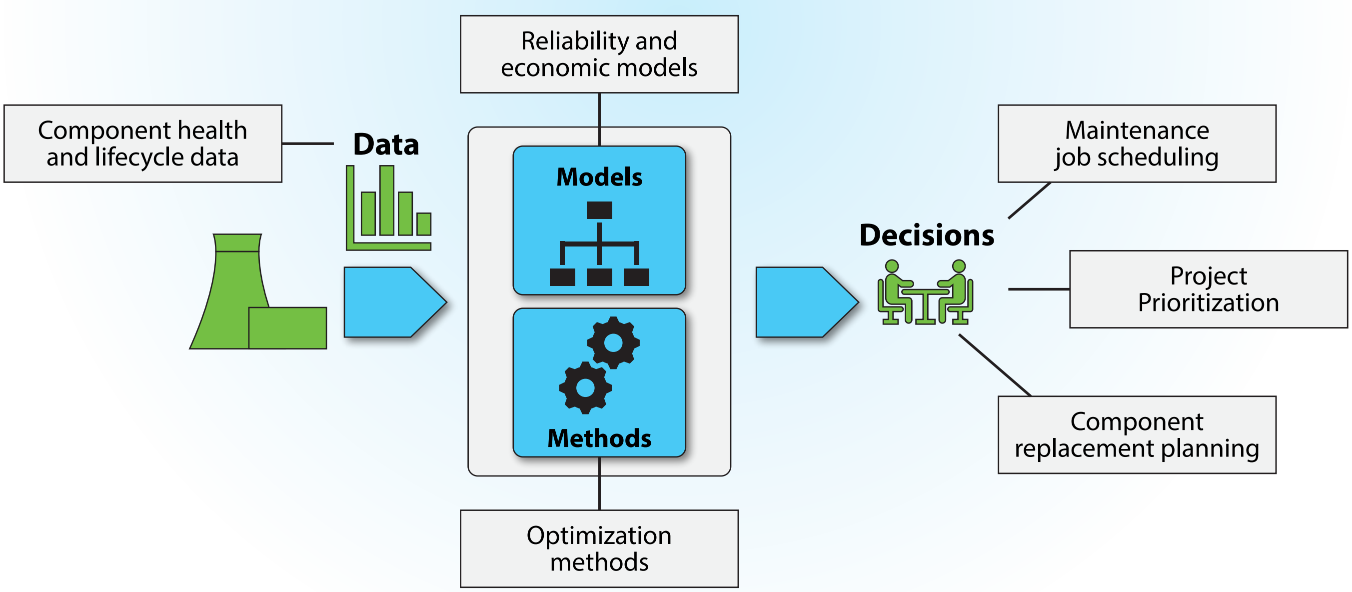
Ivilina T. Popova
Texas State University

Stephen M. Hess
Jensen-Hughes

Industry Equipment Reliability (ER) and Asset Management (AM) Programs are essential elements that help ensure the safe and economical operation of nuclear power plants. The effectiveness of these programs is addressed in several industry developed and regulatory programs. For example, all U.S. nuclear power plants have implemented the ER process defined in Institute of Power Operations AP-913 "Equipment Reliability Process Description." Additionally, performance of plant structures, systems, and components (SSCs) is monitored within a regulatory context in the Maintenance Rule 10 CFR 50.65 and the Mitigating Systems Performance Index programs. However, these programs have proven to be labor intensive and expensive. There is an opportunity to significantly enhance the collection, analysis, and use of this information to provide more cost-effective plant operation. Additionally, there is an acute industry need to leverage advanced technology to reduce costs and improve operational effectiveness.

The goal of the RISA Pathway [1] is to provide effective and efficient analytical methods and tools to support risk-informed decisions for the ER and AM programs at nuclear power plants. This is accomplished by creating a direct bridge, see Figure 11, between component health/lifecycle data and decision-making (e.g., maintenance scheduling, project prioritization and actuation planning). Here we are supporting typical system engineering decisions regarding maintenance activity scheduling and component aging management. This is performed in a risk-informed context where herein the term "risk" is

Figure 11. Graphical representation of the enterprise risk-analysis framework: from data to decisions.



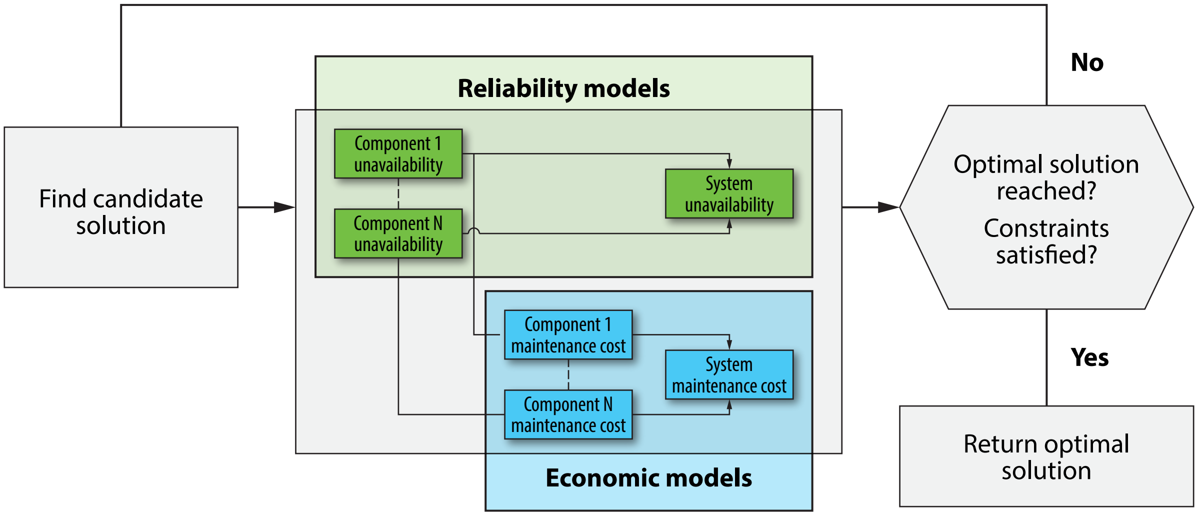


Figure 12. Example of a workflow that integrates economic and reliability models to obtain optimal solution (e.g., optimal component replacement schedule)

broadly constructed to include both plant reliability and economics. The vision is to reduce plant operations and maintenance costs by automating this decision process, by evaluating the reliability and economic impact of different maintenance strategies (i.e., evaluate what-if scenarios), and by identifying the optimal maintenance posture that maximizes system reliability and minimizes operational costs (i.e., maximize the maintenance value given resource constraints).

The final outcome of this project is an enterprise risk-analysis framework, which can be deployed across the nuclear industry. This framework combines data analytics tools to analyze ER data with risk-informed methods designed to support system engineer decisions (e.g., maintenance and replacement schedules, optimal maintenance posture for plant systems) in a customizable workflow. A challenge is that the structure of this workflow strongly depends on the decision that needs to be made, the type of data available, and the constraints that need to be considered. Current methods are designed to provide specific answers to specific problems; however, these methods might prove to be inadequate even when problem settings slightly change (e.g., different types of constraints, additional dependencies between system reliability and economics). We tackled this challenge by designing the framework in a flexible and modular fashion such that the user can assemble and customize his/her own workflow that integrates SSC economic lifecycle models (e.g., maintenance and replacement costs), system reliability models, and optimization methods (see Figure 12).

In January 2021, the first step toward the development of this framework was taken when two software packages, which are an integral part of the enterprise risk-analysis framework, were released with an open source license: LOGOS and SR2ML. SR2ML (https://github.com/idaholab/SR2ML) is a software package that contains a set of reliability models designed to integrate ER data (e.g., aging, testing, maintenance) and perform system-level reliability calculations [2]. LOGOS (https://github.com/idaholab/LOGOS) is a software package that contains a set of discrete optimization algorithms that can be employed to effectively manage plant assets and optimize schedules for plant operations [3]. These software packages are plugins that can be interfaced with the INL-developed RAVEN code (i.e., https://raven.inl.gov/) propagate data uncertainties (e.g., component remaining useful life), and perform data analysis and model optimization (e.g., via genetic algorithm heuristics). In this respect, SR2ML is designed to propagate ER knowledge to the system/plant level in order to identify the components that are most critical to system/plant health. LOGOS uses this information to prioritize and schedule plant operations (e.g., maintenance, testing, replacement) based on budget, reliability, and resource constraints.

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HERON: A New Tool for Assessment of LWR Operations in Future Grid Markets

Paul W. Talbot, Cristian Rabiti
Flexible Power Operation and Generation

John Taber, Robin Hytowitz
Electric Power Research Institute

The LWRS Program recently completed the demonstration of a new analysis tool that can be used to investigate options for enhancing the economic performance of existing nuclear power plants in current and future grid markets by diversifying the usage of the steam and electricity produced by these plants. This computation program, named HERON (for Holistic Energy Optimization Network), performs robust stochastic techno-economic analyses of LWR operations under both regulated and deregulated grid market conditions that progressively change over time. With the advancement of natural gas power plants and the subsidized buildup of solar and wind energy in many regions of the country, it is becoming increasingly important for owners of traditionally baseload power plants to develop strategies to operate in grid markets tending toward hour-ahead, and even minute-ahead, market decisions. HERON was specifically developed to evaluate the economic performance of flexible plant operations that include electricity production for the grid market plus energy storage or the production of other non-electrical products during specific periods of time to help raise the revenue of the nuclear plant. This mode of operation allows the nuclear plant to continue operating at its fullest capacity.

HERON's primary strength, in comparison to other grid economics analysis tools, is its focus on the capability to optimize the scale and dispatch of flexible plant operations and generation, considering multiple markets and their performance over the long-term. By predicting grid market changes over time and applying condition-dependent payments for dispatchable electricity and grid services that may become available, HERON provides insights into how the design and flexible operation of nuclear power plants can be optimized. An evaluation of case-by-case alternatives can then be made and used to develop strategies for operating nuclear power plants into the future.

The latest advancements to HERON were made in collaboration with the Electric Power Research Institute (EPRI). EPRI and LWRS Program researchers identified several policies, markets, and scenarios that LWR owners and operators may face in the next 30 years. A set of case scenarios and parameters were then developed for future markets that include 100% renewable portfolio standards, carbon tax policies, and alternate capital cost assumptions. HERON was advanced to meet the analysis demands of these scenarios. The EPRI team then applied US-REGEN (a deterministic capacity expansion model developed by EPRI, [1]) to project the marginal cost and dispatch order of generator capacity outputs. These outputs were then used by HERON to complete an analysis of the potential economic benefits of introducing hydrogen generation as an Integrated Energy System under the various market conditions. [2]

Figure 13 illustrates the concept of how a LWR may intermittently switch between the electricity market and the hydrogen market throughout a year. This is one of the scenarios of flexible operation of a nuclear plant being considered. With the goal of maximizing the revenue of the nuclear power plant, a simple "switch-over" selling price of electricity was determined for hourly scheduling of the nuclear power plant to sell power to the grid. Anytime the projected marginal electricity price exceeds the switch-over price, the plant will rapidly turn down hydrogen production and dispatch power to the grid. Conversely, when the price of electricity is projected to be low, the plant will ramp up hydrogen production. The switch-over price may vary throughout the life of the project as a function of the change in the mix of power generation capacity. With the ability to rapidly ramp hydrogen production up and down, flexible plant operations could help regulate the grid. The value of such services may become valuable in future grid markets as recognition of systems that can help stabilize and provide

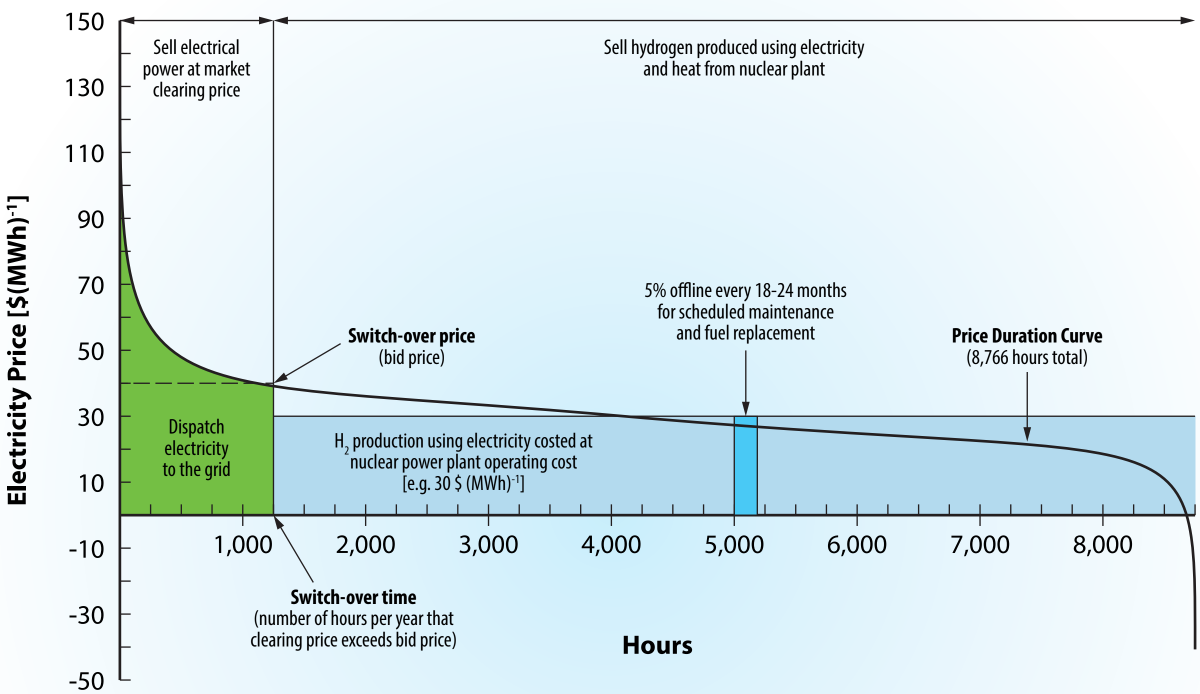


Figure 13. A sample light water reactor nuclear power plant apportionment of power to the grid and hydrogen production.

a more resilient grid is becoming evident with extreme weather events throughout the county and almost all places around the globe.

The HERON analysis of regulated and deregulated market scenarios demonstrated economic benefit to introducing hydrogen generation via flexible plant operations. In particular, if nuclear and renewable energy technology costs are expected to maintain current trajectories, substantial benefits are likely from introducing hydrogen generation as an Integrated Energy System to an existing LWR. Further, in the event of low nuclear technology costs and high variable renewable costs, and in the presence of carbon tax or 100% renewable portfolio standard policies, significant benefits are also likely from introducing hydrogen generation as an Integrated Energy System to existing LWRs.

Public release of HERON has been initiated to enable academic and commercial users to begin using this tool to evaluate new markets for LWRs. These latest improvements to HERON make it possible to evaluate various LWR plant operation options such as hydrogen production as well as the direct use of thermal energy by process industries. HERON uses data for grid market forecasts that are often available from utilities or which can be generated by capacity expansion models such as US-REGEN. The LWRS Program report for this activity provides guidance on how this is done.

References

1. U.S. Regional Economy, Greenhouse Gas, and Energy (US-REGEN) Model. Available at https://www.epri.com/research/products/000000003002016601
2. Talbot, P.W., et al. 2020. Evaluation of Hybrid Flexible Plant Operation and Generation Applications in Regulated and Deregulated Markets Using HERON. INL/EXT-20-60968, Revision 0.

LWRS Overview and Accomplishments Sustaining National Nuclear Interests Report

The LWRS Program's Report "Overview and Accomplishments Sustaining National Nuclear Interests" provides an overview of the LWRS Program and recent accomplishments that directly support the objectives of the LWRS Program (see https://lwrs.inl.gov). The following text provides a brief summary of the report.

The LWRS Program is sponsored by the U.S. Department of Energy and coordinated through a variety of mechanisms and interactions with industry, vendors, suppliers, regulatory agencies, and other industry research and development (R&D) organizations.

The LWRS Program carries out its mission to accomplish the following objectives:

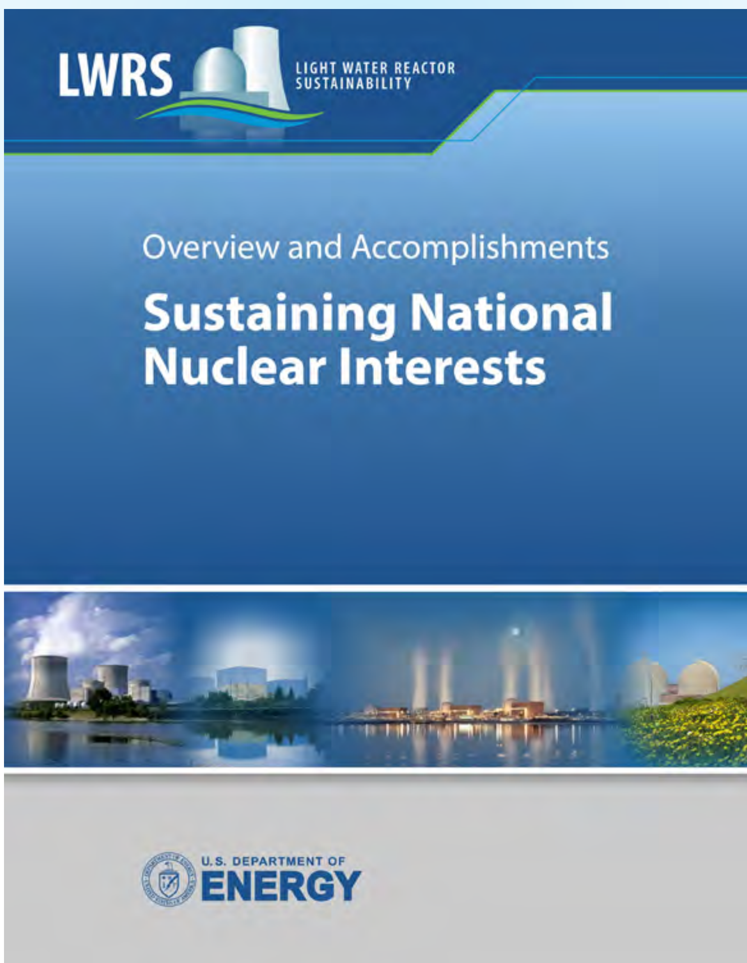
- Enhance the economic competitiveness of operating light water reactors in current and future energy markets, and;
- Ensure the performance of structures, systems, and components.

The LWRS Program, in close collaboration and cooperation with industry, provides technical foundations for the continued operation of the nation's nuclear power plants using the unique capabilities of the national laboratory system.

Sustaining the Existing Fleet

The LWRS Program focuses its research activities on two objectives needed to sustain the existing operating fleet in current and future energy markets (Figure 14).

Efforts to enhance the economic competitiveness of the existing fleet are being accomplished through research that aims to reduce the operating costs of nuclear power plants and diversify the sources of revenue available to generate income by expanding to markets beyond electricity supply.



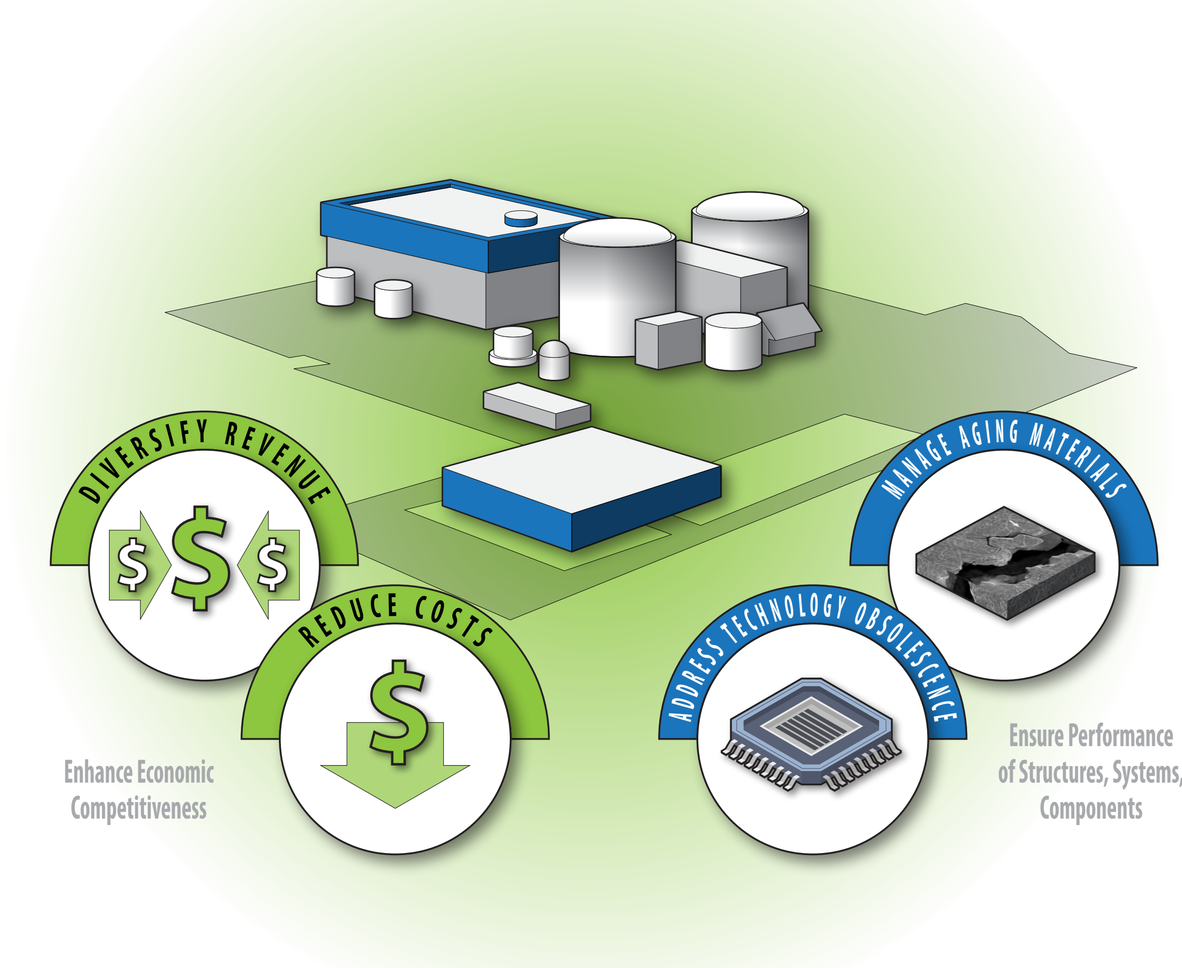


Figure 14. Paths to sustaining the existing fleet of light water reactors through collaborative research and development.

Efforts to ensure the performance of SSCs is being achieved through research to understand and mitigate the effects of environmental conditions on materials and to address the obsolescence of aging plant technologies.

The full report can be found at https://lwrs.inl.gov/Reports%20Documents/Overview_Accomplishments_Sustaining_National_Nuclear_Interests_2020.pdf

This report summarizes a number of vital collaborations that the LWRS Program conducts with stakeholders to provide foundations for continued safe and economic operation of the nation's nuclear power plants.

Recent accomplishments toward achieving these objectives are described in the report. Topics in the report include:

- Enhancing the Economic Competitiveness of the Existing Fleet
  - Research to Reduce Operating Costs and Improve Efficiencies to Enhance Economic Competitiveness
  - Research to Enable Diversification of Revenue and Expand to Markets Beyond Electricity
- Delivering the Scientific Basis for Continued Safe Operation
  - Understanding and Managing the Aging and Performance of Key Materials for Long Term Operation
  - Addressing Aging and Obsolescence of Plant Technologies

Recent LWRS Program Reports

Risk-Informed Systems Analysis Pathway

- *Terry Turbopump Expanded Operating Band Modeling and Simulation Efforts in Fiscal Year 2021 Extended Period of Performance – Final Report*
- *Development and Release of the Methods and Tools for Risk-Informed Asset Management*
- *Industry Level Integrated Fire Modeling Using Fire Risk Investigation in 3D (FRI3D)*
- *Quantitative Risk Analysis of High Safety [1]significant Safety-related Digital Instrumentation and Control Systems in Nuclear Power Plants using IRADIC Technology, INL/EXT-21-64039*
- *An Adaptable Software Toolkit for Dynamic Human Reliability Analysis: Progress Toward HUNTER 2*
- *Enhancement of Industry Legacy Probabilistic Risk Assessment Methods and Tools*
- *Demonstration of the Plant Fuel Reload Process Optimization for an Operating PWR*
- *Investigating Application of LiDAR for Nuclear Power Plants*
- *Risk-Informed Multi-Physics Best-Estimate Plus Uncertainties (BEPU): Demonstration of LOCA Scenario-Based Reflood Phenomena*
- *Technical Maturity Assessment of MOOSE-Based Tools: MASTODON, BISON and Grizzly*

Plant Modernization Pathway

- *Usability Evaluation of the Innovation Portal and Integrated Capability Analysis Platform*
- *Process for Significant Nuclear Work Function Innovation Based on Integrated Operations Concepts*
- *Scalable Technologies Achieving Risk-Informed Condition-Based Predictive Maintenance Enhancing the Economic Performance of Operating Nuclear Power Plants*
- *Development of an Assessment Methodology That Enables the Nuclear Industry to Evaluate Adoption of Advanced Automation*
- *Process Anomaly Detection for Sparsely Labeled Events in Nuclear Power Plants*
- *Digital Infrastructure Migration Framework*
- *Nuclear Work Function Innovation Tool Set Development for Performance Improvement and Human Systems Integration*

Materials Research Pathway

- *Toward an understanding of straining mode, grain boundary oxidation and localized deformation on intergranular cracking of neutron irradiated austenitic stainless steels in pressurized water reactor relevant conditions*
- *Electrochemical profiling of physical damage in nuclear core components*
- *Evaluation of Stress Corrosion Cracking Behavior of Ni-base Alloys in PWR Primary Water Containing KOH vs. LiOH*
- *Development of Digital Twin Predictive Model for PWR Components: Updates on Multi Times Series PWR Components: Updates on Multi Times Series Network, DMW Fatigue Tests, System Level Thermal-Mechanical-Stress Analysis*
- *Development of a Reconstruction Methodology Based on X-Ray Computed Tomography to Generate Realistic 3D Concrete Microstructures in MOSAIC*
- *Conduct weld campaign (FY-21-1) on irradiated materials provided by the Canadian Nuclear Laboratory (CNL), including baseline post-weld evaluation and testing*
- *Microstructure and Mechanical Performance of the Friction Stir Welds Performed on Neutron-Irradiated Steel with Helium*
- *Toward an understanding of straining mode, grain boundary oxidation and localized deformation on intergranular cracking of neutron irradiated austenitic stainless steels in pressurized water reactor relevant conditions*
- *Effect of thermal aging and irradiation on microstructure and crack growth response of Alloy 690*
- *Inhomogeneous Aging of Nuclear Power Plant Electrical Cable Insulation*
- *Sequential Versus Simultaneous Aging of XLPE and EPDM Nuclear Cable Insulation Subjected to Elevated Temperature and Gamma Radiation (FInal Results)*
- *Nondestructive Evaluation (NDE) of Cable Moisture Exposure using Frequency Domain Reflectometry (FDR)*
- *Improve the design of and assess upgrades to the Friction Stir welding system to reduce defects on surrogate unirradiated materials*

Flexible Plant Operation & Generation Pathway

- *Energy Arbitrage: Comparison of Options for use with LWR Nuclear Power Plants*
- *Evaluation of Different Levels of Electric and Thermal Power Dispatch Using a Full-Scope PWR Simulator*
- *Incorporation of Thermal Hydraulic Models for Thermal Power Dispatch into a BWR Power Plant Simulator*

(Click on the report title to download the document.)

Editor: Gordon Holt
Designer: David Combs

To submit information or suggestions, contact Cathy J. Barnard at **Cathy.Barnard@inl.gov**.

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